Bulletin of the Seismological Society of America, Vol. 70, No. 3, pp. 831-850, June 1980

TELESEISMIC SHORT-PERIOD AMPLITUDES: SOURCE AND RECEIVER VARIATIONS

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ABSTRACT

Short-period *P*-wave amplitude data from nuclear explosions in the Soviet Union recorded by WWSSN stations in the United States are presented. Thirty-four events in five test sites are analyzed. The consistency and similarity of the initial *P* waveforms allow a stable amplitude measure. A well-defined amplitude pattern is obtained for each source region. The test sites at northern and southern Novaya Zemlya show a relative amplitude trend of a factor of 3 across the United States in their respective amplitude patterns. This is in contrast to two sites at Semipalatinsk which are in good relative agreement. A pattern of lateral variation of amplitude in the United States is obtained for a northern azimuth of approach. Stations situated on sediments are corrected for amplification effects. In contrast to previous studies, stations in the Western United States do not have systematically lower amplitudes than Eastern United States stations. Lowest amplitudes are found in Golden, Colorado (GOL) and Albuquerque, New Mexico (ALQ), a factor of 4 lower than high amplitude stations. Preliminary amplitude data are presented from earthquakes in the Kuriles and South America. Events are chosen for consistency of waveforms across the United States to minimize earthquake source and directivity effects. These earthquake data indicate that amplitude variations in the United States are azimuthally dependent.

INTRODUCTION

Since the establishment of the World Wide Standard Seismograph Network (WWSSN) and during the deployment of the Long Range Seismic Measurement (LRSM) stations in the early 1960's, a number of studies have undertaken the measurement of the variation of teleseismic body-wave amplitudes in the conterminous United States. Cleary (1967) measured first-peak amplitudes of *P* waves from short-period LRSM recordings of 22 earthquakes, each having common first motions across the United States, and noted that the signal strength tended to be lower in the west than elsewhere, although exceptions did occur. Evernden and Clark (1970) and Booth *et al.* (1974) determined magnitude anomalies for stations of the LRSM and found short-period (1 sec) magnitudes in the Western United States (WUS), approximately west of the eastern front of the Rocky Mountains, are about 0.5 magnitude units (a factor of 3) smaller than the Eastern United States (EUS), east of the Rocky Mountains. Long-period magnitude (16 sec) anomalies for the LRSM show large amplitudes along the Gulf coast but no other distinct pattern (Booth *et al.*, 1974). Solomon and Toksöz (1970) used a spectral ratio technique on long-period WWSSN recordings of *P* and *S* waves from two deep focus South American earthquakes to determine apparent attenuation variation across the United States, and concluded that attenuation was higher between the Rockies and Sierra Nevada (Cascades), and the northeastern United States. Der *et al.* (1975) using short-period LRSM stations measured maximum amplitudes of *P* and *S* waves and the dominant period of *S* waves for three deep focus South American and two deep focus Kurile earthquakes and concluded that the data indicated higher attenuation in WUS than EUS. In a study using four deep focus South American earthquakes recorded by the WWSSN in the United States, Burdick (1978) utilized the ratios of short-period to long-period amplitudes of P and S waves to minimize the effect of source radiation in determining amplitude variations at the receiver. No lateral amplitude variation across the United States was seen in this data set.

The purpose of this paper is to report on the variation of P-wave amplitudes in the United States from nuclear explosions in the Soviet Union. Amplitude data from 34 nuclear explosions at five test sites are presented for 24 WWSSN stations in the conterminous United States plus BEC, Bermuda. The results are interpreted in terms of source, path, and receiver effects. Source effects are deduced by intercom-

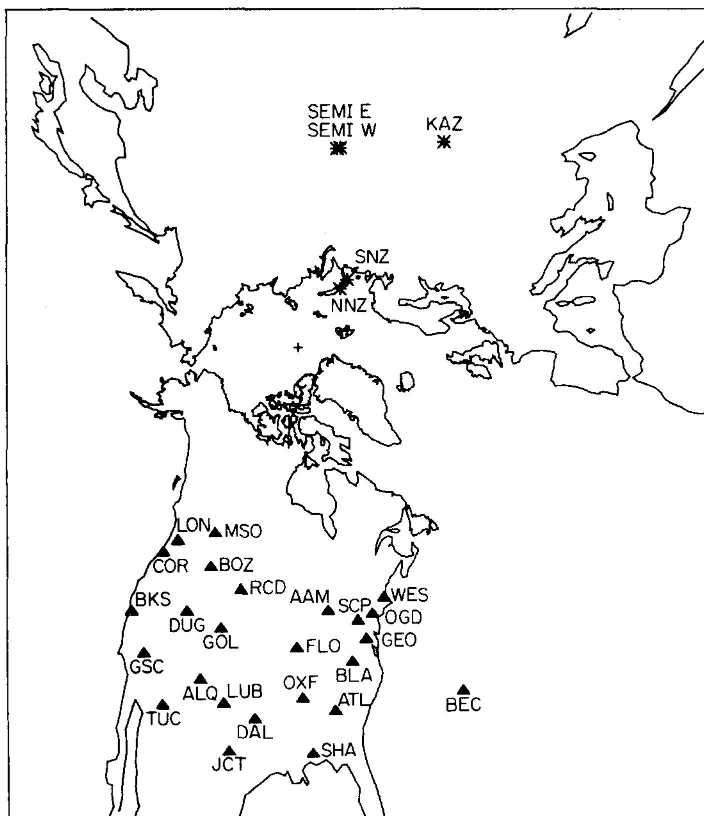

FIG. 1. A gnomic projection (all great circles are straight lines) showing the source regions in the Soviet Union and the WWSSN stations in the United States.

paring amplitude patterns among the different sites. Data which have been diffracted at the core-mantle boundary are presented, but will be discussed and interpreted in a forthcoming paper. The apparent amplitude variation in the United States for a northern azimuth of approach is determined from an average of all nondiffracted data. The effect of signal amplification for a receiver situated on low-velocity sediments is considered. A qualitative measure is made of the importance of scattering in the amplitude variation utilizing the horizontal components of the P waves. An explanation of the amplitude variation in terms of attenuation differences is considered. Finally, to provide an indication of the azimuthally varying characteristics of the amplitude pattern, preliminary results are presented in a study of amplitude patterns in the United States using earthquakes in the Kuriles and South America.

Nature of the Study

The overall geometry of the stations of the WWSSN in the United States and the source regions of the nuclear explosions in the Soviet Union are shown in Figure 1.

TABLE 1

Explosion Data Set*

Date	Time	Lat.	Long.
	Northern Novaya Zemlya		
27 Oct. 1966	5:57:58	73.44N	54.75E
21 Oct. 1967	4:59:58	73.37N	54.81E
7 Nov. 1968	10:02:05	73.40N	54.86E
14 Oct. 1969	7:00:06	73.40N	54.81E
14 Oct. 1970	6:02:57	73.31N	55.15E
27 Sept. 1971	5:59:55	73.39N	55.10E
28 Aug. 1972	5:59:57	73.34N	55.08E
12 Sept. 1973	6:59:54	73.30N	55.16E
29 Aug. 1974	9:59:56	73.37N	55.09E
23 Aug. 1975	8:59:58	73.37N	54.64E
21 Oct. 1975	11:59:57	73.35N	55.08E
	Southern Novaya Zemlya		
27 Sept. 1973	6:59:58	70.76N	53.87E
2 Nov. 1974	4:59:57	70.82N	54.06E
18 Oct. 1975	8:59:56	70.84N	53.69E
	Semipalatinsk East		
15 Jan. 1965	5:59:59	49.89N	78.97E
30 Nov. 1969	3:32:57	49.92N	79.00E
2 Nov. 1972	1:26:58	49.91N	78.84E
23 Jul. 1973	1:22:58	49.99N	78.85E
14 Dec. 1973	7:46:57	50.04N	79.01E
31 May 1974	3:26:57	49.95N	78.84E
4 Jul. 1976	2:56:58	49.91N	78.95E
23 Nov. 1976	5:03:00	50.00N	79.00E
	Semipalatinsk West		
19 Oct. 1966	3:57:58	49.75N	78.03E
20 Apr. 1967	4:07:58	49.74N	78.12E
17 Oct. 1967	5:03:58	49.82N	78.10E
29 Sept. 1968	3:42:58	49.77N	78.19E
28 Jun. 1970	1:57:58	49.83N	78.25E
22 Mar. 1971	4:32:58	49.74N	78.18E
25 Apr. 1971	3:32:58	49.82N	78.09E
30 Dec. 1971	6:20:58	49.75N	78.13E
20 Feb. 1975	5:32:58	49.82N	78.08E
	Kazakh		
6 Dec. 1979	7:02:57	43.83N	54.78E
12 Dec. 1970	7:00:57	43.85N	54.77E
23 Dec. 1970	7:00:57	43.83N	54.85E

* Locations and origin times from Dahlman and Israelson (1977).

The Russian events used in this study (listed in Table 1) have been naturally divided into several groups based on test sites. All events between 1965 and early 1976 having a yield of 70 kt or greater, are analyzed in the collection of data. The following abbreviations are used for the test sites: NNZ, northern Novaya Zemlya; SNZ, southern Novaya Zemlya; SEMI E, Semipalatinsk east; SEMI W, Semipalatinsk west; and KAZ, Kazakh. NNZ and SNZ are situated roughly 300 km apart; SEMI E and SEMI W lie about 70 km apart. The approximate distances in $\Delta°$ between the United States stations and the source regions are listed in Table 2. The United States is situated in the range 60° to 80°Δ from the Novaya Zemlya sites, NNZ and SNZ. *P* waves at these ranges bottom in the smooth lower mantle and should be relatively free of propagational path effects. The KAZ and SEMI source regions lie in the 80° to 100° range, and thus the southern United States stations will experience amplitude effects due to diffraction at the core-mantle boundary.

There are several advantages in using nuclear explosions rather than earthquakes in an amplitude study of this nature. Earthquake amplitudes contain source radia-

TABLE 2

APPROXIMATE DISTANCES BETWEEN UNITED STATES STATIONS AND RUSSIAN TEST SITES ($\Delta°$)

Station	NNZ	SNZ	SEMI	KAZ
AAM	61.2	63.2	86.9	86.5
ALQ	71.2	73.6	95.4	99.8
ATL	69.9	71.9	95.7	94.5
BEC	67.0	68.4	91.9	86.2
BKS	69.0	71.6	90.6	98.6
BLA	65.6	67.5	91.3	89.7
BOZ	60.9	63.5	84.4	90.1
COR	62.3	64.9	83.9	91.9
DAL	72.3	75.6	97.5	99.4
DUG	66.4	68.9	89.6	95.6
FLO	65.6	67.8	91.1	91.9
GEO	63.3	65.2	89.1	86.8
GOL	66.4	68.8	90.7	94.9
GSC	71.4	74.0	94.0	100.9
JCT	75.0	77.3	99.9	102.5
LON	60.1	62.7	82.0	89.7
LUB	72.1	74.5	96.8	100.1
MSO	59.8	62.4	83.0	89.2
OCD	69.7	62.5	86.5	84.0
OXF	70.0	71.8	95.3	95.5
RCD	61.8	64.3	86.3	90.9
SCP	61.6	63.5	87.4	85.6
SHA	73.2	75.3	98.9	98.4
TUC	74.1	76.6	97.6	103.1
WES	58.8	60.6	84.5	81.5

tion and directivity effects which must be corrected before amplitude effects due to the path or receiver can be ascertained. In contrast, the explosion source is theoretically spherically symmetric, and thus is naturally free of this complication. Event locations within the Soviet Union test sites vary on the order of tens of kilometers. The several events in each site allow the amplitude measurement to be repeated, and afford us an opportunity to view the stability of the measurement. Short-period vertical *P* waves are shown in Figure 2 from four event source regions. The overall consistency and similarity of the initial waveforms from station to station and event to event represent another natural advantage of the explosion data set. The initial upswing and following larger downswing are characteristic of the explosion waveform. The coherency of waveforms diminishes after this initial portion due to different crustal effects at different stations. The relative amplitude of each station within each event is indicated. There is no apparent correlation between frequency content and amplitude in this data set. Synthetic waveforms computed for the von Seggern and Blandford (1972) theoretical explosion source are shown for comparison.

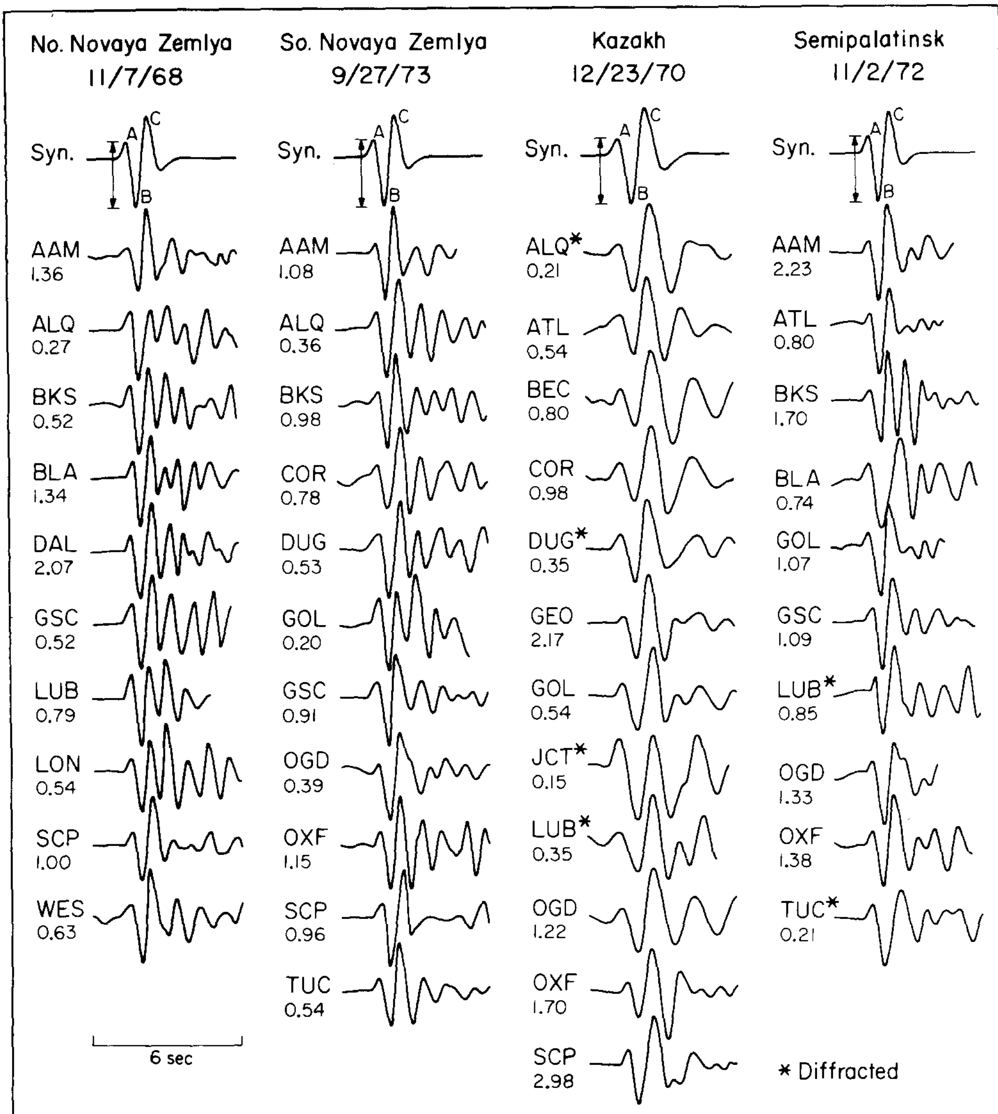

FIG. 2. Short-period P waves recorded at WWSSN stations across the United States from four Russian nuclear events. The numbers beneath the station codes indicate the true relative amplitudes as defined by the AB measure indicated on the comparison synthetic waveform. Stations beyond 95.5° are noted as diffracted.

The A and B swings are primarily controlled by the direct P wave, whereas the C peak is controlled by pP. The somewhat longer period waveform of the Kazakh event indicates a deeper depth of burial and slower rise time of the source.

The amplitude measure used throughout this study is indicated by the synthetic waveforms: the amplitude of first peak to first trough, or AB amplitude. This particular measure was chosen for several reasons. It may be consistently and unambiguously read at each station for all events. It is the portion of the waveform least contaminated by source effects due to variations in pP and source structure, and from the receiver effects of different station crustal structures. The AB amplitude measure also minimizes baseline problems in the presence of noise.

The quality of the explosion amplitude data is quite good. The amplitudes may read with a precision of better than 10 per cent, except at low gain stations for smaller events where the error may be up to 30 per cent. The data are measured, corrected to a common station gain of 100 K, and grouped by source region. In each source region are amplitude observations o_{ij} for i events and j stations. While the relative amplitude relationship from station to station is similar from event to event, the absolute amplitudes of each event are different. A simple normalization procedure would be to choose one station as a reference, and then for each event, divide all the station amplitude measurements by the amplitude at the reference station. In this way the events are normalized to a common scale but the reference station is always unity. However, this method forces whatever scatter that is characteristic of the reference station upon the rest of the stations. To improve this situation the following normalization procedure was used. From the i events, choose a reference event k, to which the other events are to be scaled in a least-squares sense. Scale factors α_i are determined such that the least-squares error is minimized for each event $i \neq k$

$$\min \sum | \alpha_i o_{ij} - o_{kj} |^2. \tag{1}$$

Let β_k be the average amplitude of the master event k

$$\beta_k = \frac{1}{j} \sum_j o_{kj}. \tag{2}$$

The total error for all events i in the source region is then

$$\frac{1}{\beta_k} \sum_i \sum_j | \alpha_i o_{ij} - o_{kj} |^2. \tag{3}$$

To iterate on the process, let each event i in a source region be the master event k. The scale factors α_i in each source are chosen for the event k which minimizes the total error (3) in the best.

DATA

The amplitude data for the five source regions are plotted in Figures 3 through 6. The ordinate of each plot is a log scale indicating relative amplitude. The stations of the WWSSN used in this study are listed in a west-to-east arrangement with respect to station location in the United States viewed from the Semipalatinsk test sites. Detailed intercomparisons of the source regions will be considered in the next section but some observations may be noted at this time. The results for NNZ are shown in Figure 3. The overall scatter at each individual station is quite low; less than a factor of 1.5 about the mean. The lowest stations are ALQ and GOL, followed by DUG and BEC. The amplitudes in the west are somewhat lower than those in the east. There is an amplitude differential of nearly a factor of 5 between GOL and

ALQ and the higher amplitude stations, AAM, DAL, and SHA. The data for SNZ plotted in Figure 4 are similar in overall pattern to NNZ, but different in detail. ALQ and GOL are still low, but OGD and WES are now among the lower values. The stations in the far west for SNZ have amplitudes comparable to the high values in the central United States. The relationship of BLA with other eastern stations is

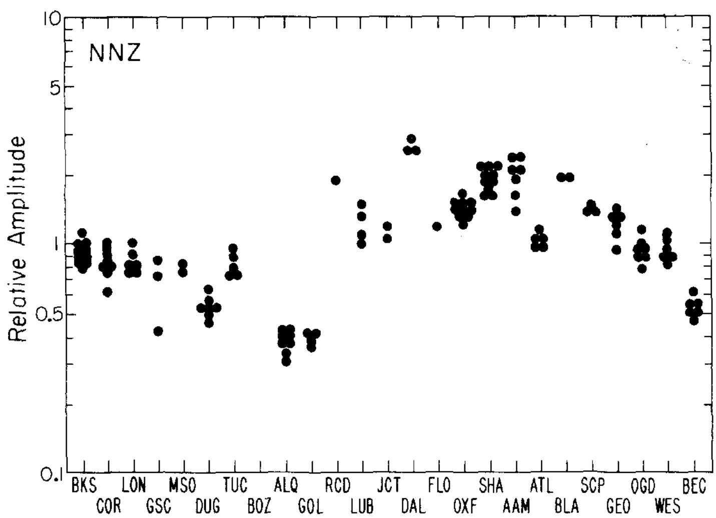

FIG. 3. Relative amplitudes of short-period P waves observed at WWSSN stations across the United States from 11 nuclear explosions at the northern Novaya Zemlya site.

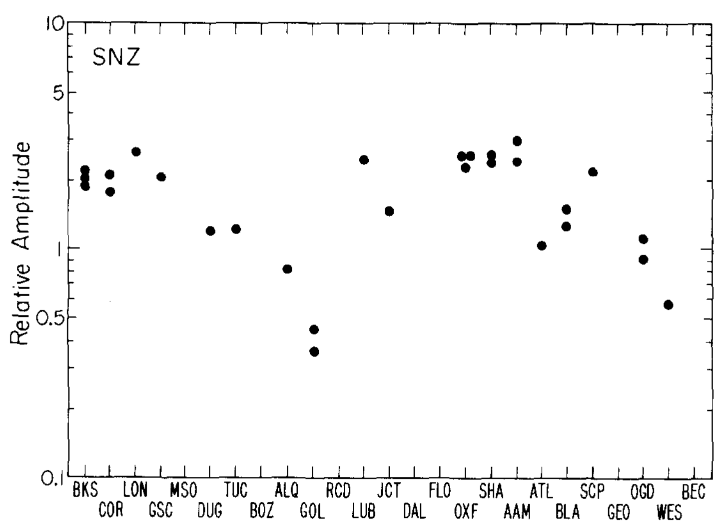

FIG. 4. Relative amplitudes of short-period P waves observed at WWSSN stations across the United States from three nuclear explosions at the southern Novaya Zemlya site.

different for NNZ and SNZ. Figure 5 plots the data for both Semipalatinsk test sites. There appears to be no systematic differences between the SEMI E and SEMI W sites, in contrast to NNZ and SNZ. Figure 5 is considerably more complicated in appearance than the plots for the Novaya Zemlya source regions. The greater scatter at the individual stations may come in part from including stations showing amplitude diffraction effects (TUC, DAL, LUB, and JCT) in the data normalization

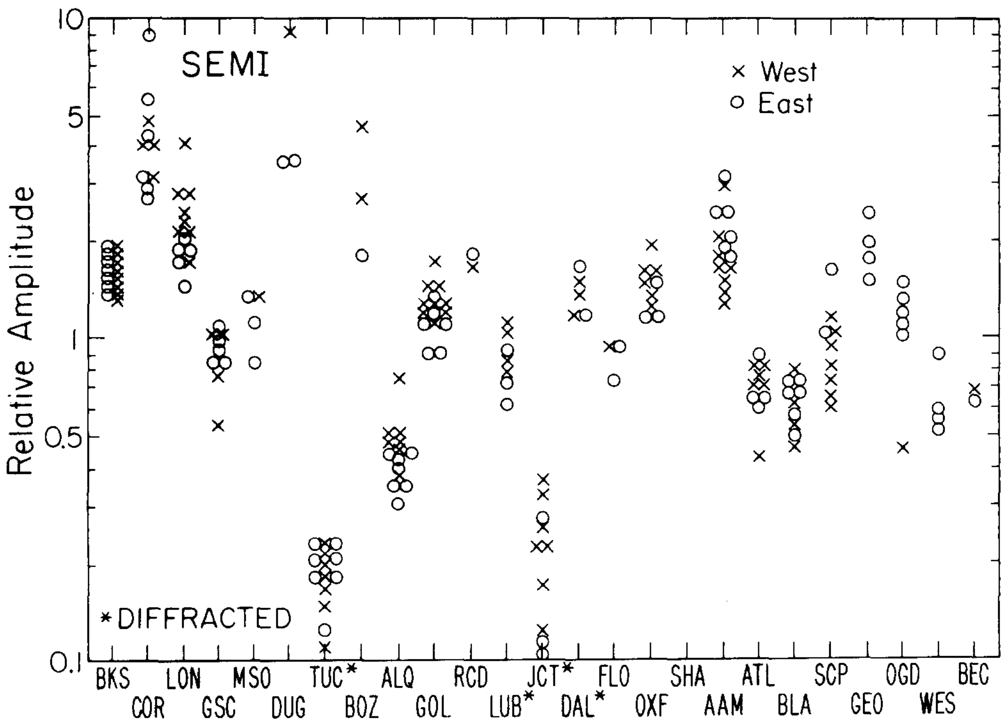

FIG. 5. Relative amplitudes of short-period P waves observed at WWSSN stations across the United States from 17 nuclear explosions at the east and west Semipalatinsk test sites. Stations beyond 95.5° are noted as diffracted.

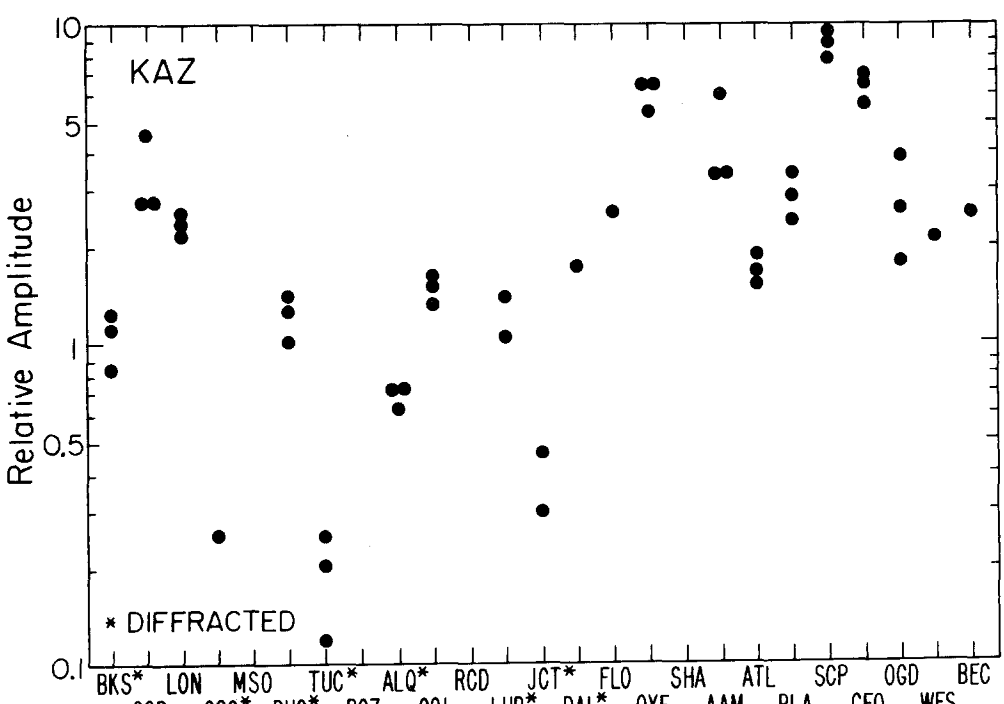

FIG. 6. Relative amplitudes of short-period P waves observed at WWSSN stations across the United States from three nuclear explosions at the Kazakh site. Stations beyond 95.5° are noted as diffracted.

procedure, and in part from larger reading errors in measuring the amplitudes of the smaller yield Semipalatinsk explosions. Stations COR, DUG, and GOL show greater relative amplitudes from the Semipalatinsk sources than were observed for NNZ and SNZ. The three events for the Kazakh site are plotted in Figure 6. Low individual station scatter is observed for this site. A number of stations, BKS, GSC, DUG, TUC, ALQ, LUB, JCT, and DAL, show relative deamplification due to diffraction at the core-mantle boundary.

SOURCE COMPARISONS

The amplitude patterns in Figures 3 through 6 represent a combination of source, path, and receiver effects. The effect of the receiver may be removed to look at the

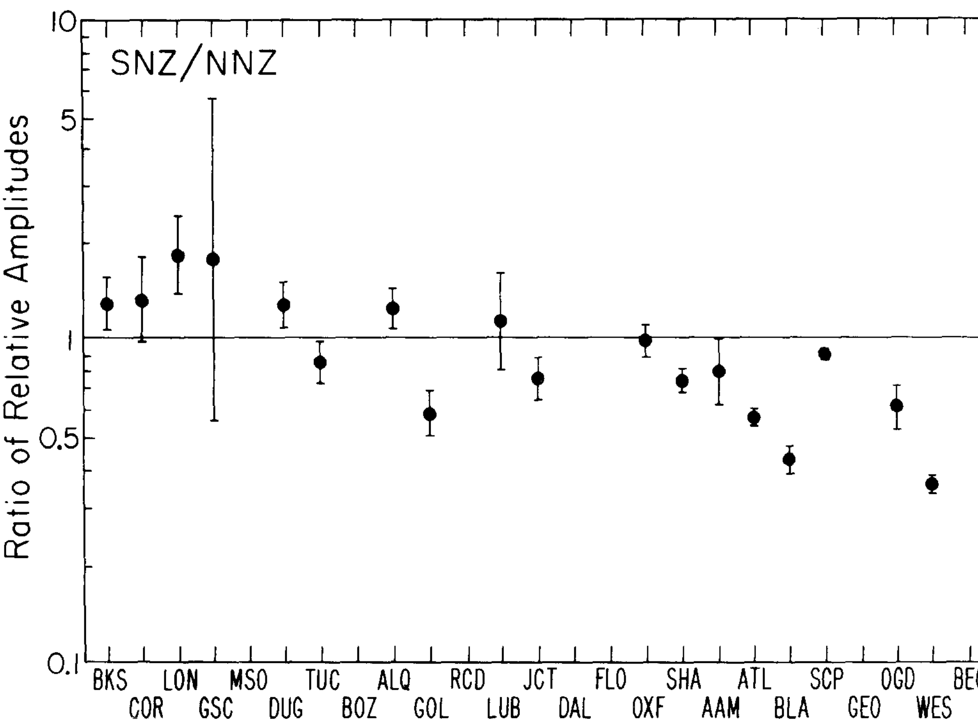

FIG. 7. Ratio of the amplitude pattern for the southern Novaya Zemlya site to the amplitude pattern for the northern Novaya Zemlya site.

effects due to the source and the path if it is assumed that P waves emerging at a station in the United States from the different test sites experience a common receiver effect. As the azimuths and angles of incidence from the five source regions vary by only several degrees, this is a plausible assumption. The mean and standard error of the mean are calculated from the event data at each station for the different source regions and are used in further manipulation of the data. Dividing the station amplitude values for one test site by those of another cancels the common receiver and smaller geometric spreading effects. The resultant ratios may be plotted in the same fashion as Figures 3 through 6 and represent the relative source-path effects between the two source regions. In the case of the two Novaya Zemlya sites, NNZ and SNZ, as the ray paths are similar and bottom in the rather smooth lower mantle, the ratio pattern represents primarily relative source effects. This ratio pattern is plotted in Figure 7 from the data in Figures 3 and 4. The figure shows an unmistakable trend of high in the west to low in the east, roughly a factor of 3 variation. As the ratios indicate only a relative pattern, the amplitude variation could originate at NNZ or SNZ, or a combination of both. To attempt to clarify this point, intercomparisons with the SEMI and KAZ sites are tried.

To utilize SEMI and KAZ for source and receiver consideration, stations suffering amplitude diminution due to diffraction at the core-mantle boundary must be separated. The diffraction effect is considered in detail in a separate paper (Ruff and Butler, in preparation) but may be briefly outlined. The SEMI and KAZ data are ratioed to the NNZ and SNZ data. The ratios are then plotted amplitude versus distance. The ratios hover about unity until the distances from SEMI and KAZ reach about 95.5°Δ. Past this distance, amplitudes systematically decline due to diffraction. Stations showing this amplitude diminution have been indicated in Figures 5 and 6 with an asterisk. These stations are largely deleted from further

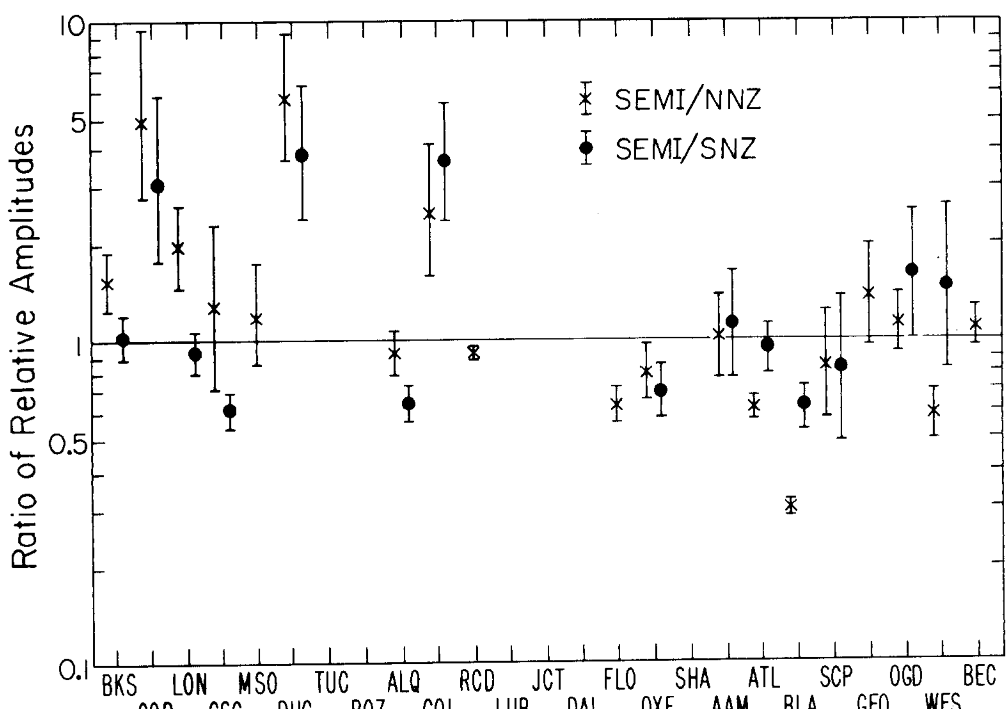

FIG. 8. Ratios of the amplitude pattern for the combined east and west Semipalatinsk sites to the amplitude patterns for the northern and southern Novaya Zemlya sites. Diffracted data have been deleted.

consideration in this paper. Stations less than 95.5° shall be assumed to be free of diffraction amplitude effects.

An interesting contrast is observed between the two sites of Semipalatinsk and the two sites on Novaya Zemlya. The scatter observed at a station for the different events at the Novaya Zemlya sites in Figures 3 and 4 is low, and is somewhat greater for Semipalatinsk. This increased scatter in the SEMI values may be partly due to including the diffraction data in the normalization. More interesting, however, is the overall agreement of SEMI E with SEMI W, in marked contrast to the differences observed in the ratio plot of the SNZ to NNZ. The two SEMI sites lie about 70 km apart, while SNZ and NNZ are roughly 300 km apart. A ratio comparison among the combined SEMI data and NNZ and SNZ is shown in Figure 8. If COR, DUG, and GOL are momentarily ignored, the remaining SEMI stations fit the NNZ and SNZ data equally well with a scatter of less than a factor of 2. This also appears to be the case in the KAZ data in Figure 9, although the control is more sparse. The scatter of the KAZ values in relation to NNZ and SNZ is of the same order as was observed in Figure 8 for Semipalatinsk, somewhat less than a factor of 2.

The SEMI stations COR, DUG, GOL, and the NNZ value for BLA show a considerably larger deviation than the other stations in Figure 8 and importune a momentary digression to consider these anomalous values further. For additional comparison, a ratio plot of the KAZ data to NNZ and SNZ is shown in Figure 9. In this plot, neither COR or GOL show large deviations, and quite the contrary, agree well with the NNZ and SNZ values. DUG is included though it may be somewhat

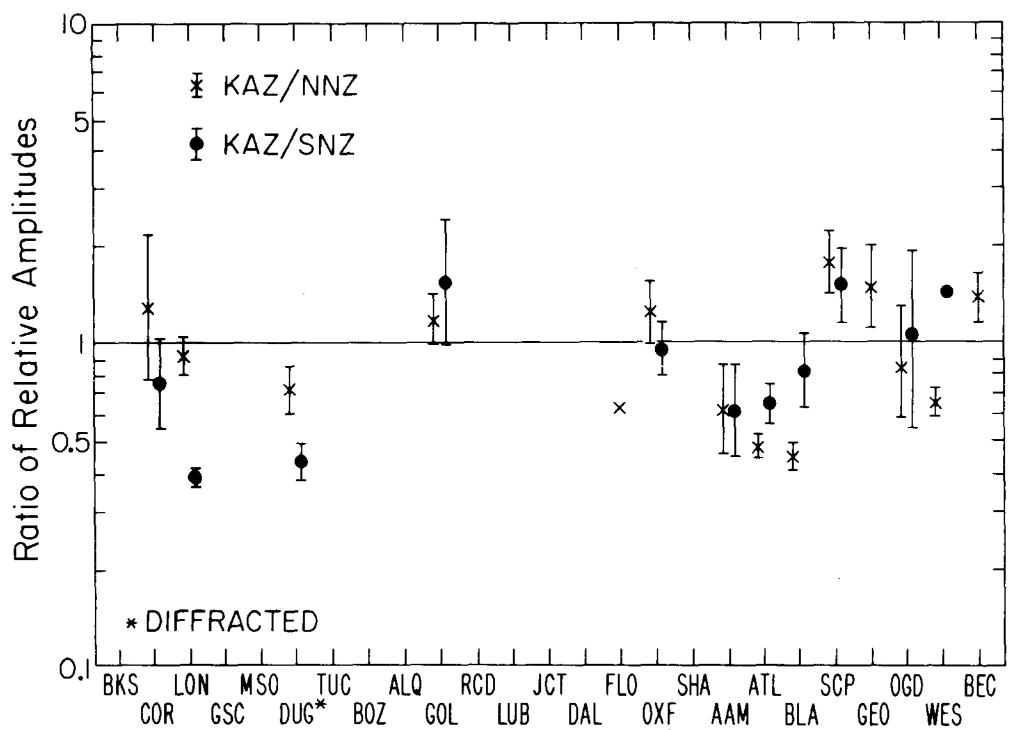

FIG. 9. Ratios of the amplitude pattern for the Kazakh site to the amplitude patterns of the northern and southern Novaya Zemlya sites. Diffracted data, except DUG, have been deleted.

diminished due to diffraction, to show that it does not stand greatly different than the NNZ or SNZ data. This suggests that the apparent amplification of COR, DUG, and GOL is a property of the SEMI data set. As this amplification is observed for only these three stations in both the SEMI E and SEMI W data, and as the two sites are situated 70 km apart, and ruling out coincidence as low probability, it is concluded that the apparent amplification is not due to the source regions, but rather rests in path or receiver effects. Other stations to be noted in Figure 9 are LON and BLA. LON has shifted from favoring SNZ at SEMI to favoring NNZ for the KAZ data. The amplitude value for BLA at NNZ is a factor of 2 or more greater than the values for BLA at the other test sites and most likely represents an anomaly in the NNZ source region.

Station COR at Corvallis, Oregon, together with LON in Longmire, Washington, have been studied by Burdick and Langston (1977), Langston and Blum (1977), and

Langston (1977, 1978) who analyzed long-period body waveforms in the determination of receiver structure. Both COR and LON have been found to show receiver anomalies which may be partly attributable to dipping structure. A comparison of the *P* waveforms of COR and LON with the other WWSSN stations in the United States for this explosion data set qualitatively reveals greater complexity for the vertical and horizontal components for both long- and short-period *P* waves at COR and LON. It seems likely then that the amplification at COR for the SEMI source regions, and possibly some of the scatter at LON, may be due to lateral heterogeneity at the receiver.

As DUG and GOL are adjacent stations such that their ray paths occur close together, the apparent amplification at these two stations may be caused by a common velocity anomaly affecting both paths. Otherwise, an appeal is necessary to separate receiver anomalies that affected both stations in a similar fashion from the same approach azimuth. The discussion of a common velocity anomaly is deferred to the companion study.

On the basis of the intercomparisons of the test sites, our qualitative results may be summarized. The two sites at Novaya Zemlya show a relative amplitude trend of a factor of 3 across the United States in their respective amplitude patterns. This is in contrast to the two test sites at Semipalatinsk, where they are in good relative agreement. This amplitude anomaly associated with Novaya Zemlya does not appear to be a local function of either NNZ or SNZ, as the amplitude patterns for KAZ and SEMI are intermediate between NNZ and SNZ. No information is available in the geophysical literature to help to resolve this issue. Geologically, the islands of Novaya Zemlya are a continuation of the Ural Mountains, and as such are part of a suture zone between ancient European and Asian plates. The complex geological structure observed on geology maps of the Urals and Novaya Zemlya are circumstantially supportive, but offer no additional information to aid our interpretation.

Amplitude Variation at Receiver

In the previous section, amplitude data for the five test sites were intercompared using a ratio technique which essentially eliminated common receiver effects. In this section, the amplitude data from the five test sites are plotted together to look for systematics of the common receiver effect. Stations showing amplitude diffraction effects and the amplitude values of three anomalous stations for the Semipalatinsk data (COR, DUG, and GOL) have not been included in the common plotting. Although some systematic differences among the various source regions were found in the previous sections, the data from each site are included without any corrections, understanding that the source region differences represent an inherent uncertainty in determining the effects common to the receiver. To plot the data from the different sites, the amplitude patterns in Figures 3 through 6 are characterized by the mean value of each station. The resultant amplitude patterns for the five sites are normalized in the same manner as was the event data at each site. Geometric spreading corrections have not been included as the effect is minor (about 15 per cent) compared to the variations in the data.

The amplitude data from the five Russian nuclear test sites (NNZ, SNZ, SEMI E, SEMI W, and KAZ) are plotted in Figure 10. The pattern represents apparent amplitude variations for the United States stations of the WWSSN for a northern azimuth of approach. This distinction, the northern azimuth of approach, is important as preliminary results (to be discussed in the next section) using earthquakes to view other azimuths indicate that the pattern is azimuthally dependent. However, in accepting this narrowing distinction of a northern azimuth, several observations are important. The amplitudes in the Western United States from BKS to GOL are not a consistent factor of 3 lower than amplitudes in the Eastern United States. Stations ALQ and GOL are a factor of 4 to 5 lower than the higher stations, but the other low stations in the west, DUG and TUC, have amplitude values not dissimilar from JCT, FLO, ATL, BLA, OGD, and WES. Station BEC in Bermuda also has a value comparable to DUG and TUC. The values of BOZ are quite high, albeit they represent only three events from SEMI. The remaining stations in the west, BKS, COR, LON, GSC, and MSO, share a range of amplitude values with the higher stations in the east, RCD, LUB, OXF, SHA, AAM, SCP, and GEO.

Before comparisons of a more quantitative nature can be considered, effects due to differences in the geological siting of the stations must be evaluated. Gutenberg

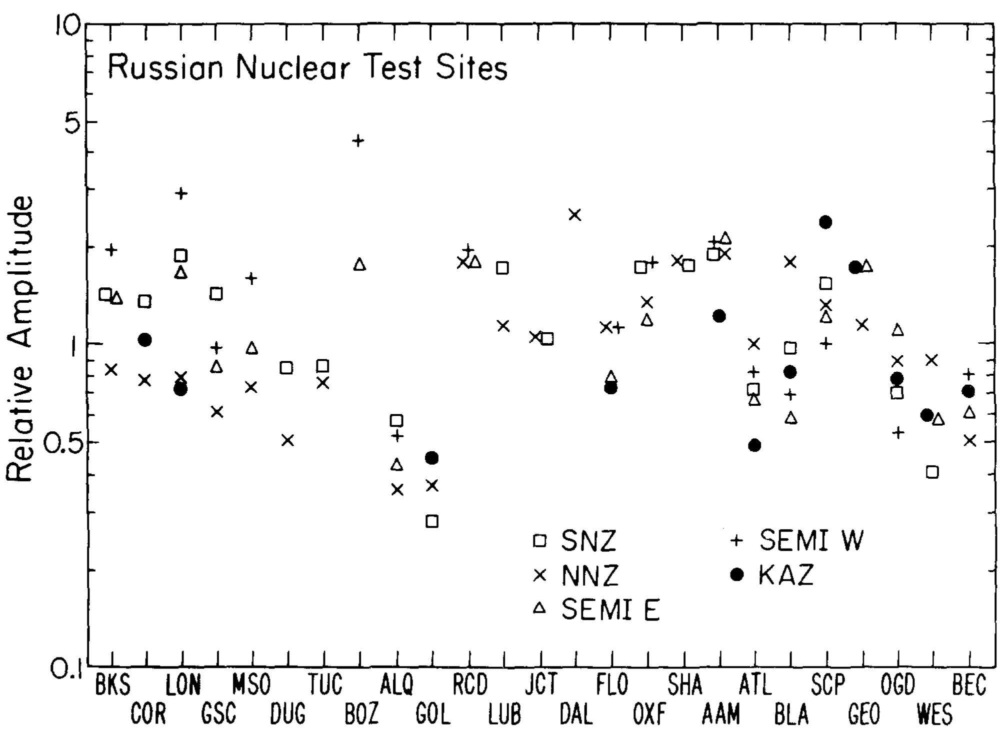

FIG. 10. Combined plot of the amplitude data from the southern and northern Novaya Zemlya, east and west Semipalatinsk, and Kazakh sites for WWSSN stations across the United States. The mean of the amplitude data at each station for each site is plotted. Diffracted and anomalous (see text) data have been deleted.

(1956, 1957) and Borcherdt (1970) have noted that stations situated on low-velocity sediments are amplified relative to nearby stations situated on bedrock. Booth *et al.* (1974) invoked sediment amplification to explain high magnitude residuals for long-period LRSM stations along the Gulf coast. This sediment amplification effect is illustrated in Figure 11. The receiver effect of a variety of different sediment structures overlying bedrock are compared to simple bedrock site (*upper left*) using Thomson-Haskell propagator matrices and a synthetic explosion waveform assuming Poisson's ratio for the shear velocity and a 0.2 gm/cm^3 bedrock-sediment density contrast. Sediment thicknesses of 300 meters show appreciable amplification. Short-period P waves propagating through near surface P-wave velocities of 2 km/sec are amplified by a factor of 1.6 to 1.8 relative to bedrock; surface velocities of 3 km/sec amplify by 1.4 to 1.5. As stations in the central United States (from RCD to AAM) are situated on slower sedimentary materials in contrast to the hard-rock siting of the western and eastern coastal stations, some amplitude corrections must be made. The handbook of the WWSSN contains a short description of the local geology at each station: RCD, 2700 ft of shale, sandstone, and some limestone; LUB, Pleistocene terrestrial deposits; JCT, Cretaceous Edwards limestone; FLO, 50 to 60 ft of recent clay overlying Mississippian bedrock; OXF, 2100 ft of Cenozoic and Mesozoic sediments; SHA, sands and gravels of Plio-Pleistocene age underlain by clays and sand of Miocene age; AAM, 200 ft of gravel, 800 ft of shale, and 4800 ft of limestone. Composing a velocity section from the geological descriptions is somewhat arbitrary.

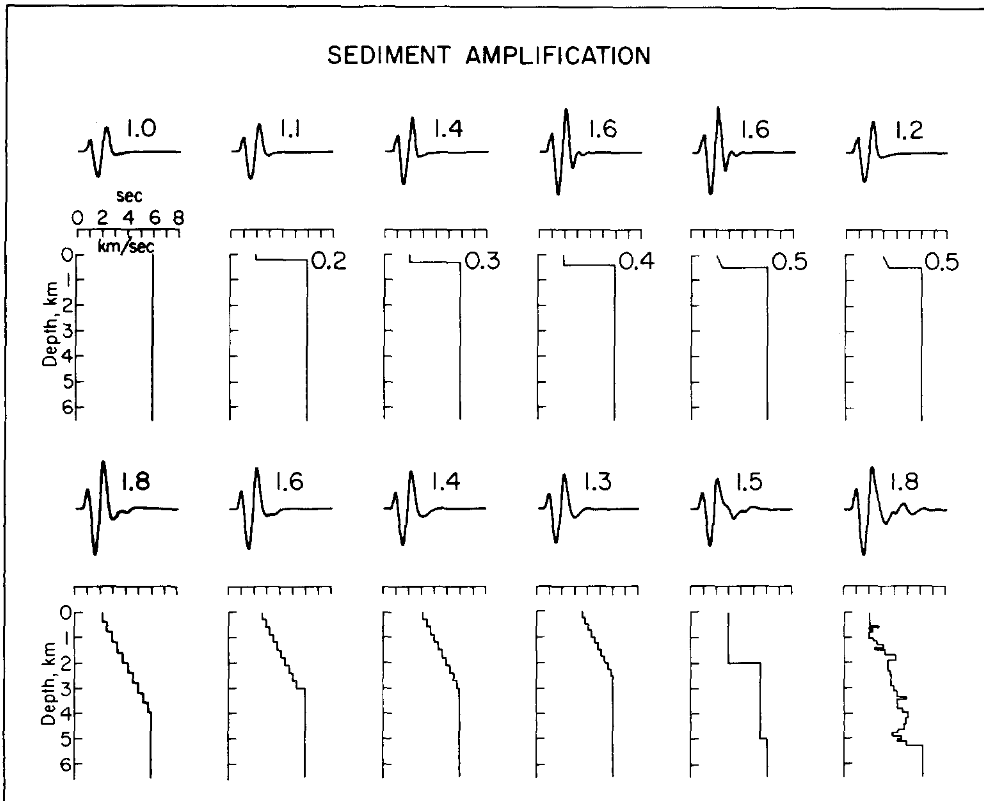

FIG. 11. Amplification effects of shallow, low-velocity sediments upon crustal models. Amplitudes noted are relative to the bedrock model in *upper left*. Sediment thickness in kilometers is indicated in *upper* models.

Shallow-lying sandstones and shales have compressional velocities from 1.4 to 3.3 km/sec. Limestone velocities are sensitive to the extent of crystallization and range between 1.7 and 6.1 km/sec (Press, 1966). Seismic refraction surveys provide only general control as sediments are grouped in a single layer characterized by the highest velocity arrival. Well-log velocity depth data provide the only accurate control, but such information was obtainable only from SHA. The lower-right velocity-depth section in Figure 11 was simplified from a well log 25 km from SHA, and shows a factor of 1.8 amplification relative to bedrock. Given the lack of velocity control in the surface layers at RCD, LUB, JCT, DAL, and AAM, only an approximate sediment amplification correction of a factor of 1.4 to 1.8 may be estimated.

Returning to Figure 10 and noting the stations in the central United States to be corrected for sediment amplification, it is observed that no pervasive factor of 3 difference in amplitude is apparent between WWSSN stations in west (left of RCD) and WWSSN stations in the central and east (right of GOL). This factor of 3 variations between the east and west is based upon studies of earthquake magnitude variations for LRSM stations in the United States by Evernden and Clark (1970) and Booth *et al.* (1974).

The amplitude variations for receivers in the United States observed in Figure 10, whether or not the pattern is azimuthally dependent, may be attributed to a number of causes. Among the more likely are variations in attenuation properties, variations in scattering properties, and focusing or defocusing due to nonplanar structure in the crust or uppermost mantle. While the focusing possibility is station-specific and cannot be modeled without more information, variations in attenuative and scattering properties may be tested for internal consistency with the data. A crude but

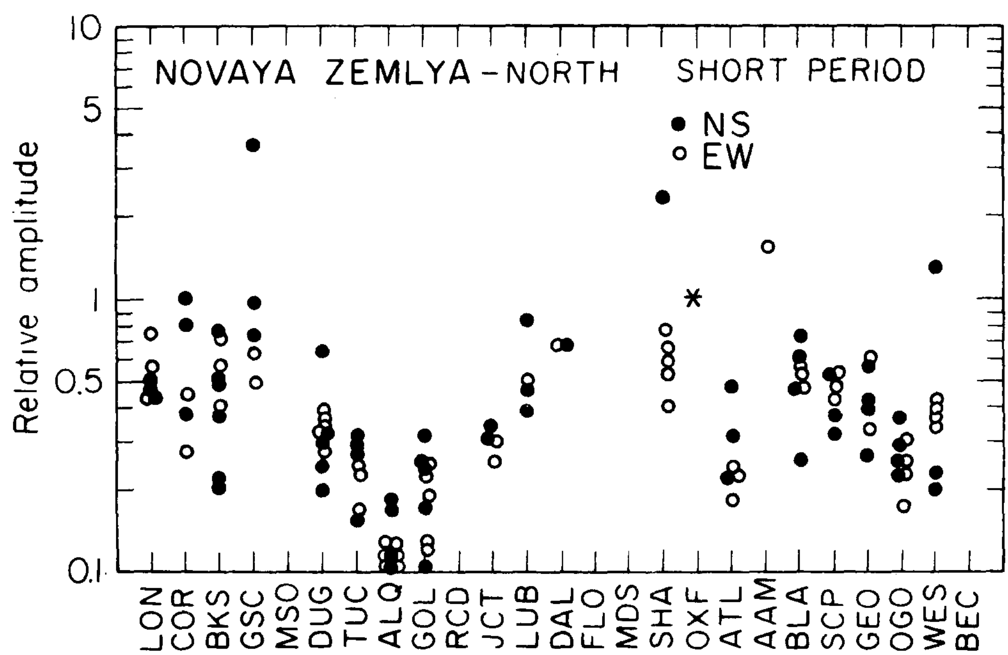

FIG. 12. Relative amplitudes of horizontal P-wave secondary arrivals (normalized to OXF) observed by WWSSN stations across the United States from 11 nuclear explosions at the northern Novaya Zemlya site.

simple test for variations of shallow crustal scattering can be made in the following manner. Consider the amplitude variations in the United States for the NNZ test site in Figure 3. For a simple scattering model, it is assumed the low amplitude stations are caused by energy scattered from the vertical component of motion. A large part of this scattered energy may manifest itself as large secondary arrivals on the horizontal components on the P-wave train. This hypothesis was tested for the events at NNZ. Amplitudes of large secondary arrivals were measured from the north-south and east-west components of the P wave. These components are approximately radial and tangential, respectively, for geometry of source and receiver. The amplitudes are normalized by the values at OXF and plotted in Figure 12 in a fashion similar to the vertical data in Figure 3. If this simple scattering hypothesis was correct, the pattern of low and high amplitudes for the vertical arrivals in Figure 3 can be expected to be reversed for the horizontal secondary arrivals; i.e., a high amplitude on the vertical would imply low amplitude on the horizontal and vice-versa. This is clearly not the case in Figure 3. Thus, the amplitude variations observed for the vertical component are inconsistent with this simple scattering test. A more sophisticated test for scattering might be to compute the total power in the horizontal coda and compare this to a maximum amplitude, but this detailed effort is beyond the scope of the present investigation.

A second possible explanation for the amplitude variations in Figure 10 is from differences in the attenuative properties along the ray paths to the stations. Assuming that attenuation is independent of frequency in the band of the WWSSN short-period instrument, variations in attenuative properties can be characterized by variations in $t* = T/Q$, the ratio of travel time to path average Q. To verify the consistency of an attenuation explanation for the amplitude variation, a large

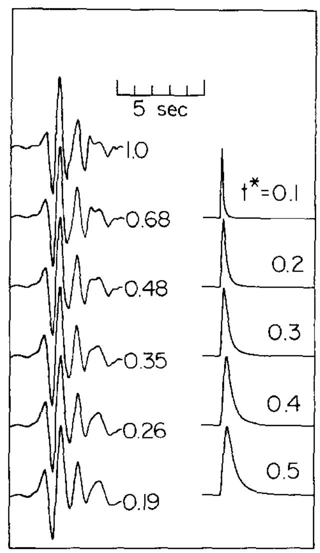

FIG. 13. Result of numerical experiment in which a high amplitude short-period P wave from a nuclear explosion is successively attenuated. The numbers following the traces indicate the signal amplitude normalized to the top trace at the *left*. The right-hand column shows the attenuation operators used to obtain each corresponding left-hand trace from the original record at *top left*.

amplitude waveform was carefully digitized and then attenuated using a Futterman (1962) attenuation operator. The results of the test are illustrated in Figure 13. The waveform and its relative amplitude are shown in the left column, and the $t*$ and shape of the attenuation operator in the right column. A factor of 5 variation in amplitude is equivalent to a $t*$ variation of 0.5 units. It is somewhat surprising that the waveforms suffering different degrees of attenuation are quite similar. Restricting our attention to the first upswing and downswing (the part of the waveform used in this study and most free of crustal complications at the source and receiver), differences due to variation in attenuation are not appreciably resolvable to be of use as a criterion in accepting or rejecting attenuation as an explanation for the amplitude variations in Figure 10. Thus, the variations of amplitudes and lack of variation in the waveforms in the Russian explosion data set are consistent with an interpretation in terms of varying attenuative properties along the ray path to the receiver.

Preliminary Results for Earthquake Sources

The study of Russian nuclear explosions has provided an interesting pattern of amplitude variations in the United States ascribable to receiver effects. However, as these data are solely from a northern azimuth of approach, it is particularly important to determine if the observed amplitude variations are azimuthally dependent. In view of the importance of this question and to temper premature speculation upon the interpretation of the explosion data, preliminary amplitude data is presented from earthquakes in the Kuriles and South America which suggest that the amplitude variations in the United States are indeed azimuthally dependent.

To simulate the study of the explosion data set and to overcome as best as possible the problems of earthquake source radiation and directivity, a selection of earthquakes were sought to satisfy the following criteria: the short-period P waveforms must be simple, of short duration, explosion-like in character, and similar at all

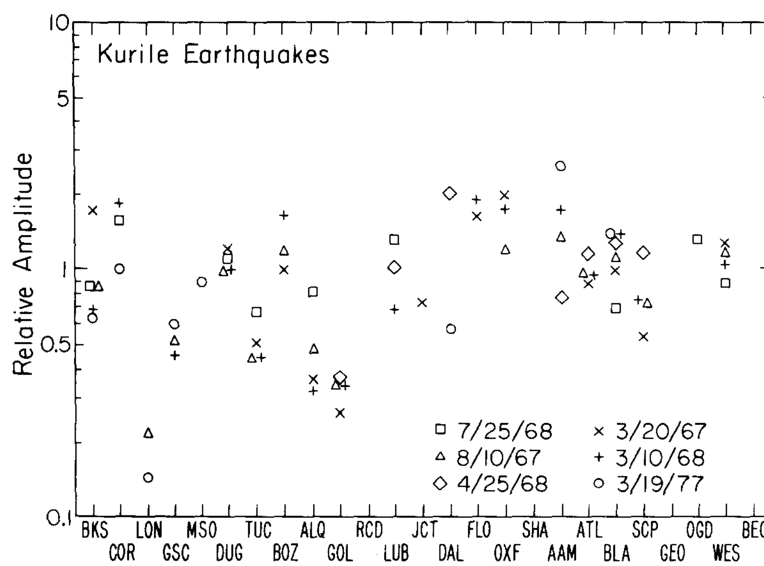

FIG. 14. Relative amplitudes of short-period P waves observed by WWSSN stations in the United States for six earthquakes in Kurile Islands. The events were selected to minimize earthquake source radiation and directivity effects.

stations recording the event in the United States. Two source regions were considered in the search: events in the Kurile Islands and South America.

A systematic search of earthquakes in the two regions occurring between 1965 and 1968 and between September 1976 and May 1977 yielded six Kurile events and eight South American events of acceptable nature. Amplitudes were measured and normalized in the same manner as the Russian explosion study.

The earthquake data for the Kuriles is plotted in Figure 14 in the same manner as the explosion data. The low scatter of the event data at the individual stations suggests that source radiation and directivity effects are minimal. The azimuth to the Kurile earthquakes roughly lie N45° W of the Russian test sites, and a good deal of consistency is seen comparing Figures 10 and 14. Figure 15 plots the average values of Russian explosion data together with the Kurile earthquake data for better comparison. Except for LON which was noted earlier to be associated wih anomalous receiver effects, the Kurile data lie within a factor of 2 of the Russian explosion data.

A plot of the eight South American earthquakes is shown in Figure 16. The scatter at the stations is again quite low. The South American events lie nearly opposite in azimuth to the Russian explosion data, and considerable differences between the two regions may be observed. ALQ and GOL are no longer the lowest amplitude stations, but now fall in the range of the other west and east coast stations. Amplitudes in the central United States are considerably larger than values of east

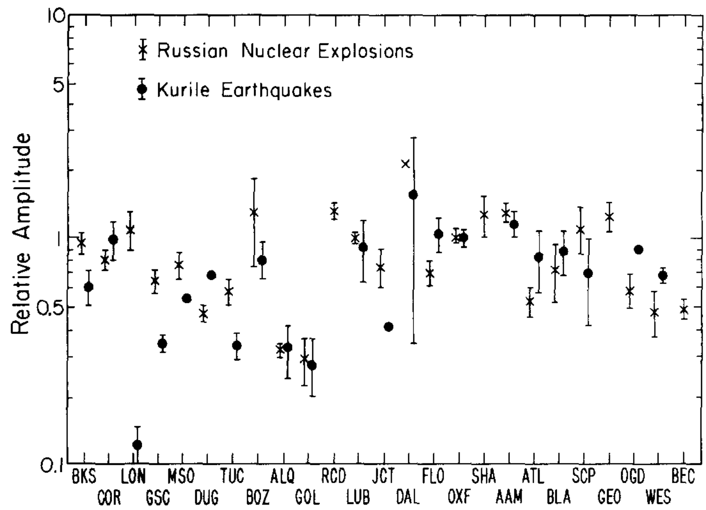

FIG. 15. Comparison of the amplitude pattern from the combined Russian explosion data with the amplitude pattern from the Kurile Island earthquakes.

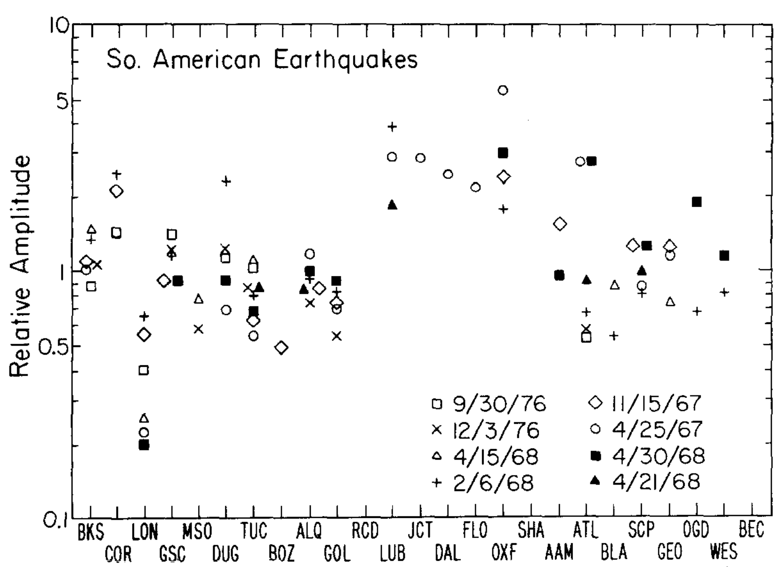

FIG. 16. Relative amplitudes of short-period P waves observed by WWSSN stations in the United States for eight earthquakes in South America. The events were selected to minimize earthquake source radiation and directivity effects.

or west, but there are not enough data yet to preclude anomalous source effects. The amplitude data from earthquakes in the Kuriles and South America are quite interesting. The waveform criteria in selecting events yield amplitude data with low internal scatter and appear to minimize amplitude effects from the source radiation and directivity. The relative agreement between the Kurile data and the Russian explosion data indicates that the amplitude variation pattern in the United States is stable with moderate changes of azimuth. However, differences between the South American earthquakes and the Russian explosion data suggest that the total azimuthal variation is quite pronounced at some stations. Further discussion of azimuthal differences in the amplitude variations of WWSSN stations in the United States must await a more detailed study. However, the preliminary results presented herein suggest considerable promise in the ability to approach the azimuthally dependent amplitude variation problem.

SUMMARY

The study presented is an analysis of the short-period amplitude behavior of WWSSN stations in the United States recording underground nuclear explosions in the Soviet Union. There is a well-defined relative amplitude pattern for any one Russian test site, and additionally, the relative amplitude patterns observed at the United States stations are quite similar for the various test sites. This is an indication that the relative differences among the United States stations are primarily due to effects near the receiver. These initial results concerning the coherence of short-period amplitudes and waveforms encourage a similar analysis be undertaken for all WWSSN stations.

This study may be considered a first step toward understanding the amplitudes and waveforms of short-period seismograms. The observed short-period seismograms are coherent from station to station for approximately 2 sec after the initial onset. While the relationship between relative peak heights is maintained, the absolute amplitudes can vary by nearly an order of magnitude. Stability with regard to source region seems well-documented. There is an excellent agreement between the amplitude patterns of Semipalatinsk east and west, indicating a source coherence over 70 km. However, a systematic source azimuthal difference exists between southern and northern Novaya Zemlya, a distance of 300 km. For the purpose of defining an overall amplitude pattern from the northern approach, it is encouraging to note that the values for Semipalatinsk and Kazakh lie between the values for southern and northern Novaya Zemlya.

With regard to receiver effects, although a relative amplitude pattern is well-defined for the Russian test sites, this pattern cannot be simply interpreted in terms of attenuation, scattering, or other mechanisms until the azimuthally varying characteristics of the relative amplitude pattern can be determined. Preliminary amplitude data presented herein from earthquakes in the Kurile Islands and South America suggest that significant azimuthal variations occur both at individual stations and for regional groupings of stations. Further work in determining the azimuthally dependent amplitude characteristics of the WWSSN stations in the United States may yield estimates of the localization of the areas of low and high amplitudes.

CONCLUSIONS

The principle results of this study are: (1) a demonstration of amplitude and waveform coherence of short-period data from Russian nuclear explosions; (2) a preliminary result concerning the azimuthal variation in the effective radiation pattern from the Russian test sites; and (3) the determination of a relative amplitude pattern across the United States, though noting the azimuthal dependence of this pattern. Additionally, possible mechanisms for the amplitude variations were examined. Amplification due to low-velocity surface sediments and diminution caused by intrinsic attenuation are viable processes in explaining the variations.

Acknowledgments

We thank Don Helmberger and L. J. Burdick for many discussions. Florence Helmberger assisted in gathering the earthquake data. Rhett Butler was partially supported by the Fannie and John Hertz Foundation Fellowship. This research was supported by the Advanced Research Projects Agency of the Defense Department and was monitored by the Air Force Office of Scientific Research under Contract F49620-79-C-0012 with Sierra Geophysics, Inc., and by Contract F49620-77-C-022 with the Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology.

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Manuscript received July 11, 1979